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PEPTIDES FOR THE TREATMENT AND DIAGNOSIS OF SYSTEMIC LUPUS ERYTHEMATOSUS

This is a continuation-in-part of co-pending U.S. Application No. 08/531,832, filed September 20, 1995, the contents of which are hereby incorporated by reference in their entirety.

Statement of Government Interest

This invention was made with government support under NIH Grant Nos. A133184, AR32371, PO1AI33184, and CA39838. As such, the government has certain rights in this invention.

Background of the Invention

Systemic lupus erythematosus (SLE) is a chronic, inflammatory, often multisystemic disease which can be acute or insidious in onset. SLE is marked by a wide variety of abnormalities, including arthritis and arthralagias, nephritis, central nervous system manifestations, pleurisy, pericarditis, leukopenia or thrombocytopenia, and hemolytic anemia. One of the most serious complications of SLE is lupus nephritis. Renal involvement usually occurs early in the course of the illness and is the leading cause of death in SLE patients.

Diagnosis of SLE is made on the basis of a number of clinical symptoms such as the so-called "butterfly rash," an erythematous rash which frequently appears on the cheeks of afflicted individuals, crossing the bridge of the nose and becoming more pronounced upon exposure to sunlight; and arthritis which can affect any joint system. However, diagnosis is difficult to verify without appropriate laboratory tests. In this regard, antibodies directed to double-stranded DNA (dsDNA) are diagnostic of SLE and serum titers correlate with disease activity in both humans and mice (Pearson et al., J.Immunol. 126:16 (1981)).

Although the role of DNA as the significant target antigen of the so called "anti-dsDNA antibodies" which are diagnostic of SLE, is controversial, it is

accepted that the anti-dsDNA antibodies play a significant part in the pathogenesis of the disease, especially its nephritic manifestations, e.g. a secreted form of an anti-dsDNA antibody encoded on a transgene was shown to cause SLE-like glomerulonephritis in a nonautoimmune mouse (Tsao et al., J.Immunol. 149:350 (1992)). Furthermore, the high level and wide variety of autoantibodies against nuclear constituents, especially DNA, and cytoplasmic cellular components detectable in afflicted individuals suggests that the disease represents a failure of the regulatory mechanisms of the autoimmune system that sustain self-tolerance and prevent the body from attacking its own cells, cell constituents, and proteins.

Currently, there is no uniform treatment available for SLE. The choice of treatment regimen usually is determined by the individual patient's symptomatology and health status. There is thus the need for a uniform treatment regimen, especially for the nephritic manifestations of SLE.

The present invention provides a method for identifying peptide sequences which bind to anti-dsDNA antibodies. The present invention also provides peptide sequences which define epitopes recognized by pathogenic murine anti-dsDNA antibodies. The present invention also provides an accurate and rapid method of detecting anti-dsDNA antibodies and of diagnosing SLE which can used by unskilled individuals. The methods of detection and diagnosis of the present invention are based on the detection of the complexes formed between the anti-dsDNA antibodies present in a biological sample and one or more of the peptides of the present invention. The present invention further provides a method of treating SLE using one or a mixture of two or more of the peptides of the present invention to block the harmful results which occur whenever the anti-dsDNA antibodies interact with their target in vivo.

Summary of the Invention

The present invention provides a method for identifying a peptide which binds to an anti-double stranded DNA antibody which comprises: (a) contacting a peptide library composed of randomly generated peptide sequences with an anti-double stranded DNA antibody; (b) detecting the formation of a complex between the anti-

double stranded DNA antibody and a peptide; (c) isolating and purifying the peptide; and (d) sequencing the peptide.

The present invention also provides a peptide which binds to an anti-double stranded DNA antibody, and provides a composition comprising at least one peptide which binds to an anti-double stranded DNA antibody.

In addition, the present invention provides methods for detecting the presence of an anti-dsDNA antibody in a biological sample and for diagnosing systemic lupus erythematosus. The methods comprise the steps of contacting a biological sample collected from a subject with at least one peptide which binds to an anti-double stranded DNA antibody and detecting formation of a complex between the peptide(s) and the anti-double stranded DNA antibody.

The present invention further provides a method for treating systemic lupus erythematosus in a subject in need of such treatment comprising administering to the subject at least one peptide which binds to an anti-double stranded DNA antibody in an amount effective to treat systemic lupus erythematosus.

The present invention additionally provides a method for treating or preventing glomerulonephritis in a subject in need of such treatment comprising administering to the subject at least one peptide which binds to an anti-double stranded DNA antibody in an amount effective to treat or prevent glomerulonephritis.

Brief Description of the Figures

Figure 1 is comprised of Figures 1A, 1B and 1C, and depicts the binding by Enzyme Linked ImmunoSorbent Assay of monoclonal antibodies R4A (Figure 1A), 95 (Figure 1B) and 52b3 (Figure 1C) to phage clones. In each figure, the shaded columns are R4A-selected phage and unshaded columns are 52b3-selected phage.

Figure 2 depicts the inhibition of R4A (1 μg/ml) binding to peptide Asp-Trp-Glu-Tyr-Ser-Val-Trp-Leu-Ser-Asn (SEQ ID NO: 1) by calf thymus DNA. Binding is measured by Enzyme Linked ImmunoSorbent Assay.

Sub C1 Figure 3 depicts peptide inhibition of R4A (1 μg/ml) binding to calf thymus double stranded DNA by Enzyme Linked ImmnunoSorbent Assay.

B Figure 4 sets forth a graph representing DWEYS (L and D peptides) (SEQ ID NO:2) inhibition of R4A binding to dsDNA. Immulon II plates were coated overnight with 100 μg/ml salmon sperm dsDNA. R4A at a final concentration of 5 μg/ml was incubated at varying concentrations of L or D DWEYS (SEQ ID NO:2) and transferred to the plate precoated with dsDNA. After a 2-hr incubation at 37°C, the plates were washed, and alkaline phosphotase-linked goat anti-mouse IgG2b antibody was added for 1 hour at 37°C. OD after addition of substrate was monitored at 405 nm.

Figure 5 sets forth kidney sections exemplifying peptide inhibition of R4A deposition in glomeruli. R4A (75 μg) and peptide (150 μg) were injected i.p. into SCID mice. Mice were killed 16 hours later, and the kidneys immunostained for IgG deposition. Figure 5A shows a representative sample from a mouse injected with R4A, and the R4A- specific L peptide DWEYS (SEQ ID NO:2). Figure 5B sets forth a representative section from a mouse injected with R4A, and the R4A- specific D peptide DWEYS (SEQ ID NO:2). More anti-dsDNA antibody is present in glomeruli from mice injected with the L peptide.

Detailed Description of the Invention

The present invention provides a method for identifying peptides which bind to anti-double stranded DNA antibodies. According to the method of the present invention, peptides which bind to anti-double stranded DNA antibodies are identified by screening a peptide library with an anti-double stranded DNA antibody and detecting the formation of complexes between the anti-double stranded DNA antibody and the peptides contained in the library. Peptides thus detected are isolated and purified and their amino acid sequence determined.

The anti-double stranded DNA antibodies used to screen the peptide library in the method of the present invention may be animal or human and are preferably human. The anti-double stranded DNA antibodies may be generated by a number of methods known to one skilled in the art. For example, human monoclonal anti-double stranded DNA antibodies may be produced by Epstein Barr virus (EBV)

transformed cell lines derived from patients suffering form SLE. Mononuclear cells are isolated by centrifugation of peripheral blood lymphocytes, bone marrow or spleen cells obtained from SLE patients. The mononuclear cells are mixed with an EBV-infected Marmoset cell line. The transformed cells which result from this procedure are cloned. The monoclonal antibodies produced by the EBV-transformed cell lines may be tested for DNA reactivity by a number of methods known to one skilled in the art, e.g. labeled DNA made double stranded by filtration through nitrocellulose filters, is incubated with antibody and the amount of label retained by the filter measured to assess DNA binding by the antibody (Mannheimer-Lory, et al., J.Clin.Invest. 87:1519-1525 (1991)).

The peptide libraries used in the method of the present invention contain peptides composed of variable, randomly-generated peptide sequences. The peptides may be of uniform or non-uniform length. The peptide libraries may consist of amino acids of either the L- or D-optical isomer form, or a combination thereof. Such libraries may be prepared by a number of procedures known in the art. These procedures may involve the use of peptides produced by the application of recombinant DNA technology as outlined in the Experimental Details Section which follows. For example, oligonucleotides of random sequence are inserted into a phage gene so that the peptide encoded by the oligonucleotide is expressed during the lifecycle of the phage. Alternatively, the peptides may be synthesized by automated means such as the peptide synthesis systems manufactured and supplied by Applied Biosystems (Foster City, Ca). Such peptide synthesis systems are well known to one skilled in the art, e.g. Synergy Personal Peptide Synthesizer (Model 432). The synthetic peptide libraries may be composed of D- or L- amino acids. A D- peptide library may be made synthetically by procedures known to those skilled in the art for making L- peptide libraries, however, when constructing the library, D- amino acids would be substituted for L-amino acids.

The peptide library may be screened using the anti-double stranded DNA antibody by methods well known in the art, e.g., immunoprecipitation. Such methods are discussed in greater detail below. Several isotopic (e.g. ^{125}I) and nonisotopic (e.g.

chemiluminiscent) means may be used to detect complex formation between the peptide and the anti-double stranded DNA antibody. Other means of detection would be apparent to one skilled in the art.

Once a particular phage has been identified as encoding a peptide which binds to an anti-double stranded DNA antibody, the peptide is isolated by separating the peptide from the antibody (e.g., by using denaturing conditions), and purified by standard techniques well known to one skilled in the art such as conventional chromatographic techniques. Following isolation and purification of the peptide, its amino acid sequence can then be determined. Means for determining the amino acid sequences of peptides are well known in the art, e.g., the Microsequence Analysis System - Model 476A (Applied Biosystems).

The present invention also provides a class of peptides which bind to anti-double stranded DNA antibodies and are detected by the above-outlined method. These peptides are between about 5 and about 50 amino acids in length, and may be between about 5 and about 30, about 5 and about 15, about 5 and about 13 and about 5 and about 10 amino acids in length. Shorter peptides are preferred for diagnostic and therapeutic applications. The peptides of the present invention are monomers with amino acids joined through amide bonds. In the context of this specification, the amino acids may be the L- or D-optical isomer. Standard abbreviations for amino acids are used herein (e.g. Pro for Proline). These abbreviations are included in Stryer, Biochemistry, Third Ed. (1988) which is incorporated herein in its entirety by reference.

One peptide of the present invention binds to human anti-dsDNA monoclonal antibodies and contains the general amino acid sequence X-Gly-Trp-X-Arg-Val (SEQ ID NO:3) wherein X represents any amino acid known in the art. Thus examples of the peptides of the present invention include but are not limited to peptides with the following amino acid sequence:

B Trp-Gly-Trp-Thr-Arg-Val; (SEQ ID NO:3)

B Leu-Gly-Trp-Val-Arg-Val (SEQ ID NO:3); and

B Phe-Gly-Trp-Thr-Arg-Val (SEQ ID NO:3)

Another peptide of the present invention binds to human anti-double stranded DNA monoclonal antibodies and contains the general amino acid sequence X-Trp-X-Tyr-His-X (SEQ ID NO:4) wherein X represents any amino acid sequence known in the art. Thus examples of the peptides of the present invention include but are not limited to peptides with the following amino acid sequence:

Trp-Trp-Val-Tyr-His-Pro (SEQ ID NO:4); and

Tyr-Trp-Tyr-Tyr-His-Trp (SEQ ID NO:4)

Another peptide of the present invention binds to mouse anti-double stranded DNA monoclonal antibodies and contains the general amino acid sequence X1-Trp-X1-Tyr-X2 (SEQ ID NO:2) wherein X1 is Asp or Glu, and X2 is Gly or Ser. Thus the present invention includes peptides with the following amino acid sequence:

Asp-Trp-Asp-Tyr-Gly (SEQ ID NO.2);

Asp-Trp-Glu-Tyr-Gly (SEQ ID NO.2);

Glu-Trp-Asp-Tyr-Gly (SEQ ID NO.2);

Glu-Trp-Glu-Tyr-Gly (SEQ ID NO.2);

Asp-Trp-Asp-Tyr-Ser (SEQ ID NO.2);

Asp-Trp-Glu-Tyr-Ser (SEQ ID NO.2);

Glu-Trp-Asp-Tyr-Ser (SEQ ID NO.2); and

Glu-Trp-Glu-Tyr-Ser (SEQ ID NO.2)

Another peptide of the present invention binds to mouse anti-dsDNA monoclonal antibodies and contains the general amino acid sequence X1-Gly-X1-Trp-Pro-Arg (SEQ ID NO:5) wherein X1 is Asp or Glu. Thus the present invention includes peptides with the following amino acid sequences:

Asp-Gly-Asp-Trp-Pro-Arg (SEQ ID NO:5);

Glu-Gly-Asp-Trp-Pro-Arg (SEQ ID NO:5);

Asp-Gly-Glu-Trp-Pro-Arg (SEQ ID NO:5); and

Glu-Gly-Glu-Trp-Pro-Arg (SEQ ID NO:5)

The peptides of the present invention may be synthesized and purified by a number of established procedures known in the art such as the so-called "Merrifield" solid phase peptide synthesis described in Merrifield, J.Am.Chem.Soc. 85:2149-2154

(1963). Solid phase synthesis techniques have been provided for the synthesis of several peptide sequences on substrates such as "pins" (See, Geysen et al., J.Immun.Meth. 102:259-274 (1987)). Other solid-phase techniques involve synthesis of various peptide sequences on different cellulose disks supported on a column (See Frank and Doring, Tetrahedron 44:6031-6040). Peptides may also be synthesized using automated peptide synthesizers, e.g. Peptide Synthesizer - Model 431-A (Applied Biosystems).

The peptides of the present invention may be conjugated to a variety of molecules such as detectable markers and toxins or may be synthesized as polymers. Methods for conjugating peptides to such molecules are well known in the art. Suitable detectable markers include but are not limited to radioactive markers such as ^{125}I, fluorescent markers such as fluorescein, and enzymic markers such as horseradish peroxidase. Suitable toxins include but are not limited to Cholera toxin, Diphtheria toxin, Pertussis toxin, E.coli heat-labile toxin, E.coli heat-stable toxin, Botulinum toxin, Tetanus toxin, and the adenylate cyclases of Bordetella pertussis and Bacillus anthracis, and any other molecules which are capable of destroying or inactivating any cells or molecules which contain a receptor which binds to the peptides of the present invention. Such cells and molecules include but are not limited to B cells and antibodies.

The present invention also provides a composition comprising one or a mixture of two or more peptides which bind to anti-double stranded DNA antibodies. In a preferred embodiment, the composition of the present invention comprises one or a mixture of two or more peptides together with a pharmaceutically or physiologically acceptable carrier. Such compositions may be prepared by adding one or a mixture of two or more peptides to the pharmaceutically or physiologically acceptable carrier. Suitable pharmaceutically or physiologically acceptable carriers include but are not limited to water containing physiologically compatible substances such as sodium chloride, glycine, and the like, having a buffered pH compatible with physiological conditions to produce an aqueous solution, and rendering said solution sterile. In another embodiment, one or a mixture of two or more peptides can be mixed or otherwise made compatible with buffers and reagents known to those skilled in the art

in order to facilitate their use in in vitro applications such as diagnostic assays for SLE antibodies.

The present invention also provides a method for detecting the presence of anti-double stranded DNA antibodies in a biological sample. The method of the present invention comprises contacting the biological sample with one or a mixture of two or more peptides and detecting complex formation between the peptide(s) and anti-double stranded DNA antibodies, if present in the sample. A biological sample may be a bodily fluid e.g., blood or saliva, or a secretion, e.g., sweat or tears. The biological sample may be collected by any means known to those skilled in the art for collecting such samples, e.g., venipuncture in order to obtain a blood sample.

Immunochemical assays for detecting anti-dsDNA antibodies using one or a mixture of two or more peptides can be conducted using a variety of techniques known in the art. For example, a liquid phase assay can be used wherein the peptide(s) and the biological sample are mixed and allowed to form complexes in solution. The complexes so formed can be detected by a number of methods well known in the art. For example, complex formation can be monitored by sodium dodecyl sulphate (SDS) polyacrylamide gel electrophoresis (PAGE) (Davis et al., Basic Methods in Molecular Biology, 2nd. ed., (eds. Appleton & Lange), Section 17-2 (1994)).

Alternatively, a solid phase assay can be used. In the solid phase assays the peptide(s) identified by the method described above is immobilized on a solid phase to form an antigen-immunoadsorbent. The immunoadsorbent is incubated with the biological sample. After an appropriate period of incubation, the immunoadsorbent is separated from the sample (by, for example, sedimentation or centrifugation) and complex formation detected by standard procedures known in the art, e.g., labeled anti-(human IgG) can be used to detect anti-dsDNA antibodies in a biological sample obtained from a human subject. The amount of label associated with the immunoadsorbent can be compared to positive and negative controls to assess the presence or absence of anti-dsDNA antibodies.

The immunoadsorbent can be prepared by adsorbing or coupling peptide(s) to a solid phase. A variety of different types of solid phase can be used,

e.g., beads formed of glass, polystyrene, polypropylene, or dextran. Other suitable solid phases include tubes or plates formed from or coated with these materials. Attachment of peptide(s) to the solid phase can be accomplished by covalent or non-covalent bonding techniques, e.g., covalent bonding via an amide or ester linkage or adsorption. After the peptide(s) is affixed to the solid phase, the solid phase can be post-coated with an animal protein, e.g., 3% fish gelatin, in order to reduce nonspecific adsorption of protein to the immunoadsorbent surface.

The immunoadsorbent is then incubated with the sample to be tested for the presence of anti-dsDNA antibodies. If blood is being screened, then the plasma or serum components can be used. For example, the plasma or serum is diluted with normal animal plasma or serum. The plasma or serum diluent is preferably derived from the same animal species that is the source of the anti-(human IgG) antibody. Anti-(human IgG) antibody can be prepared from a variety of sources known in the art, e.g., sheep or goat. The incubation conditions (e.g., pH, temperature, time of incubation) are not crucial and such parameters can be optimized by routine experimentation by one of ordinary skill in the art.

After incubation and separation of the immunoadsorbent from the biological sample, the immunoadsorbent is incubated with the labeled anti-(human IgG) antibody to detect the presence of anti-dsDNA antibodies bound thereto. Detection can be accomplished by a number of methods known in the art, e.g., the immunoadsorbent is incubated with anti-(human IgG) antibody which is labeled with a radioactive material such as ^{125}I; or labeled with an optical label such as a fluorescent material; or labeled with an enzyme such as horseradish peroxidase. The anti-human antibody can also be biotinylated and labeled avidin used to detect its binding to immunoadsorbent.

Depending upon the choice of label, the evaluation of the presence of anti-dsDNA antibodies can be determined in a variety of ways. Label can be detected by a gamma counter if the label is a radioactive gamma emitter, or by a fluorimeter, if the label is a fluorescent material. In the case of an enzyme, label detection may be accomplished colorimetrically using an enzyme substrate.

For convenience and standardization, reagents for the performance of the various types of immunometric assays made possible by the use of the peptides which bind anti-dsDNA antibodies can be assembled into assay kits. For example, a kit for screening blood for the presence of anti-dsDNA antibodies would include: an immunoadsorbent, e.g., a polystyrene bead coated with a peptide(s); a diluent for the serum or plasma sample, e.g., normal goat serum or plasma; an anti-(human IgG) antibody, e.g., goat anti-(human IgG) antibody in buffered, aqueous solution containing about 1% goat serum or plasma; a positive control; and a negative control. If the label is an enzyme, an additional element of the kit could be the substrate for the enzyme.

The present invention also provides a method of diagnosing SLE which comprises obtaining a biological sample, contacting the biological sample with one or a mixture of two or more peptides using standard procedures already described and well known to those skilled in the art. Complex formation between one or a mixture of two or more of the peptides and antibodies contained in the biological sample is diagnostic of SLE. In particular, such complex formation is indicative of the nephrotoxicity associated with SLE.

The method of the present invention can be used to diagnose SLE in a human or animal, and is preferably used to diagnose SLE in a human. The method of the present invention can specifically be used to determine which patients will develop kidney disease. The biological sample may be obtained and complex formation monitored using the procedures described above.

The present invention also provides a method for treating SLE. In a preferred embodiment of the present invention, the peptides are capable of neutralizing antibodies which are important in the pathogenesis of SLE. Neutralization of the antibody activity occurs as a result of the formation of a stable complex between peptide and antibody molecule or as a result of conformational changes in the antibody molecule which are caused by the binding of peptide and antibody.

The present invention additionally provides a method of preventing or inhibiting binding of anti-dsDNA antibodies to glomeruli of renal tissue. Antibodies to dsDNA deposit in the glomeruli of the renal tissue in kidneys of SLE patients, causing

glomerulonephritis. In one embodiment of the invention, D-peptides are used to treat or prevent binding of anti-dsDNA antibodies to glomeruli of renal tissue. In a specific embodiment of the invention, the D-peptide DWEYS (SEQ ID NO. 2) prevents binding of anti-dsDNA antibodies to glomeruli. The D- peptide DWEYS (SEQ ID NO. 2) forms a complex with the glomerulotropic R4A antibody and prevents its deposition in the kidney.

Compositions comprising one or a mixture of two or more peptides which bind anti-dsDNA antibodies in combination with pharmaceutically or physiologically acceptable carriers may be prepared as described above and administered using procedures known to one skilled in the art such as intravenous, intramuscular, subcutaneous, or intraperitoneal routes of administration. Other modes of administration would be apparent to one skilled in the art.

The peptide(s) contained in the composition can be protected against degradation by proteases *in vivo* by a number of methods known to one skilled in the art, e.g., by increasing the concentration of peptides in the peptide composition; more frequent administration of the peptide composition; and chemical protection of peptide(s) using protective groups well known to those skilled in the art of peptide chemistry. Such protective groups will preferably protect the peptide from the effects of proteases and will not interfere with the antibody-peptide binding reaction.

The effective amount of peptide composition and the decision to use a single peptide or a mixture of two or more peptides will depend upon the individual subject being treated. Peptide(s) can be delivered to their site of action in slow-release vehicles known in the art such as liposomal preparations. Such slow-release vehicles can be injected or implanted using surgical procedures. The precise manner of delivery will be dependent upon the subject being treated and such will be obvious to one skilled in the art when presented with the individual subject. The peptides may also be used in polymeric form to induce B cell tolerance.

The present invention is described in the following Experimental Details Section, which sets forth specific examples to aid in an understanding of the invention, and should not be construed to limit in any way the invention as defined in the claims which follow thereafter.

Experimental Details Section

I. Materials and Methods

A. Isolation of Antibodies

Standard hybridoma technology was used to fuse spleen cells from a BALB/c mouse immunized intraperitoneally with phosphorylcholine (PC) (Sigma, Chemical Co., St. Louis, MO) conjugated to human gamma globulin in Complete Freund's Adjuvant PC coupled to keyhole limpet hemocyanin (KLH) (100 μg). The monoclonal antibody R4A is encoded by the germline S107 V11 H chain gene and a germline V_k1 L chain gene (Shefner et al., J.Ex.Med. 173:287-296 (1991)). SCID mice given R4A cells in vivo display proteinuria and dense immunoglobulin deposition in glomeruli (Scott, et al., Proc. Natl. Acad. Sci. 89:5398-5402 (1994)).

The 52b3 monoclonal antibody was obtained by performing site-directed mutagenesis on the R4A progenitor resulting in three amino acid differences in FR3 of the H chain: Arg was changed to Gln at position 55, Thr was changed to Ala at position 82b and Arg was changed to Ser at position 83. 52b3 shows a 10-fold greater dsDNA binding than R4A. Although SCID mice given 52b3 cells develop proteinuria and display mild antibody deposition in glomeruli, they also have marked deposition in renal tubules.

The 95 monoclonal antibody was obtained by performing site-directed mutagenesis on the R4A progenitor generating a single amino acid change in CDR3 of the H chain: Asp was changed to Gly at position 95. 95 shows no detectable dsDNA binding and SCID mice given 95 cells show no antibody sequestration in glomeruli and no disease.

B. Construction of a Peptide Library

The decapeptide library L100 expressed on the minor coat protein PIII was constructed using the vector fUSE5 (Scott and Smith, Science 249:386-390 (1990)) with the amino-terminus ~~NH_2-Ala-Asp-Gly-Ser-Gly-Gly-X-$_{10}$-Gly-Ala-Pro-Ser-Gly-Ala-Glu-Thr-Val~~ B' using standard methods.

B

Ins B'

C. Isolation of Antibody-Bound Phage Clones

Library screening was performed using modifications of the technique described by Scott and Smith, supra. Three or four rounds of affinity selection were performed. Antibody was incubated for 4 hours with gentle agitation with an aliquot of phage library in 100 μl of biopanning buffer (10 mM Tris/HCl pH 7.5, 150 mM NaCl, 0.1% w/v BSA, 0.1% v/v Tween 20, 0.02% w/v NaN_3). Antibody concentration was 1 μM for the first round and 10 nM for the subsequent rounds of biopanning.

For the first round of biopanning, 50 μl of streptavidin coated magnetic beads (Advanced Magnetics, Inc., Cambridge, MA) were incubated with 100 μl of 5 μM biotinylated protein G (Pierce, Rockford, IL) for 1 hour at room temperature with agitation. In subsequent rounds of biopanning 10 μl of streptavidin beads and 0.05 μM of biotinylated protein G were used. To saturate the streptavidin sites on the beads, 1μl of free D-biotin 10 mM (Sigma Chemical Co., St. Louis, Mo) was added and incubated for 15 minutes at room temperature with continued agitation. Beads were washed three times with 500 μl of biopanning buffer (BPB) using an Eppendorf magnetic particle concentrator (DYNAL, Oslo, Norway).

The streptavidin bead/biotinylated protein G complex was combined with the phage library/antibody mixture and incubated for 30 minutes at room temperature with agitation. Beads were collected and unbound phage were removed by washing. Phage were eluted with 100 μl of 0.1M glycine pH 2.2 for 10 minutes and neutralized with 10 μl 2M Tris pH 9.0.

Eluted phage were amplified on E.coli K91Kan (Scott, et al., supra) and used as input in the subsequent rounds of biopanning. After three or four rounds individual phage clones were randomly selected for sequencing using Sequenase Version 2.0 (United States Biochemical, Cleveland, Ohio) and fUSE ^{35}S sequencing primer. Sequencing was performed according to the dideoxy chain termination method of Sanger, et al. (Sanger et al., PNAS 74:5463-5467 (1977)).

D. Enzyme-Linked ImmunoSorbent Assay

Binding of antibodies to phage was determined by Enzyme-Linked ImmunoSorbent Assay (ELISA). Microtiter plates (Becton Dickinson, Lincoln Park, NJ) were coated with 50 μl of antibody (1 μg/ml unless otherwise specified) in TBS (Tris/10 mM HCl pH 7.5, 150 mM NaCl) overnight at 4°C. Plates were washed 3 times with TBS/0.05% Tween 20. Approximately 2.5×10^{10} purified phage in 50 μl TBS were added to each well, incubated for 2 hours at 37°C, washed, and then were blocked with 150 μl of TBS/2% BSA for 1 hour at 37°C. Plates were incubated with 50 μl of a 1:4000 dilution in TBS of biotinylated sheep antibody to M13 phage (5'->3', Inc., Boulder, CO) for 1 hour at 37°C. Plates were washed again and incubated with a 1:4000 dilution of alkaline phosphate-conjugated streptavidin (Southern Biotech. Assoc. Inc., Birmingham, AL) and developed with Sigma-104 substrate tablets (Sigma Chemical Co.). Optical density was read at 405 nm.

E. Peptide Synthesis

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Both the L- and D- form, amidated, acetylated peptides ~~Asp-Trp-Glu-Tyr-Ser-Val-Trp-Lys-Ser-Asn,~~ (SEQ ID NO:7) B2 Asp-Trp-Glu-Tyr-Ser (SEQ ID NO:2), and Arg-His-Glu-Asp-Gly-Asp-Trp-Pro-Arg-Val were synthesized in the Macromolecular Analysis Facility at the Albert Einstein College of Medicine.

F. Assay of Anti-dsDNA Antibody Glomerular Deposition

Glomerular deposition of the nephritogenic R4A antibody was examined by injecting purified antibody into SCID mice. R4A was obtained from cell culture supernatants or from ascites of mice injected with the cell line. Antibody was purified on a protein G column (Gamma Bind, Pharmacia). SCID mice were obtained from the breeding colony maintained at the Albert Einstein College of Medicine. Six- to eight-week old female mice were used in the experiments. Anti-dsDNA antibodies and IgG2b levels were undetectable in these mice before injection. Individual mice were simultaneously injected i.p. with 75 μg of purified R4A and 150 μg of the appropriate peptide. The mice were killed 16 hours after the injection of antibody.

One kidney from each animal was fixed in 10% formalin and embedded in paraffin. Four micrometer thick sections were obtained by microtome, deparaffinized, rehydrated, blocked with 2% BSA in PBS in moist chambers, and stained for 1 hour with biotinylated goat anti-mouse IgG at a 1:800 dilution at room temperature (Vector Laboratories). The sections were then incubated for 45 mins with streptavidin-alkaline phosphatase ABC reagent (Vectastain ABC kit) and developed with substrate for alkaline phosphatase (5-bromo-4-chloro-3-indoylphosphate *p*-toludine salt and nitroblue tetrazolium chloride substrate: GIBCO/BRL). Color development was stopped by the addition of distilled water. The sections were mounted on coverslips with cytosol mounting medium (Aqua polymount: Polysciences), sealed, and viewed with a Zeiss microscope.

II. Results

A. Amino Acid Motifs Are Identified by the R4A and 52b3 Anti-dsDNA Antibodies.

The monoclonal antibodies R4A and 52b3 were individually reacted with the phage library in order to obtain peptide sequences recognized by each antibody. Three rounds of biopanning were performed with R4A and four with 52b3 resulting in substantial enrichment (Table 1). Selected phage were randomly chosen for sequencing. A distinct consensus motif could be identified in each case (Tables 2 and 3). The

b dominant motif for R4A was Asp/Glu-Trp-Asp/Glu-Tyr-Ser/Gly (SEQ ID NO:7). Selected peptides had an internal cysteine bridge which presumably constrains the conformation of the internal sequence; some of these sequences also expressed the dominant motif.

b The motif identified for 52b3 is Asp/Glu-Gly-Asp/Glu-Trp-Pro-Arg (SEQ ID NO:5). Peptides with internal cysteine bridges were also isolated with 52b3, although the internal sequence of these were unlike the linear motif.

In order to confirm binding of R4A or 52b3 to these phage, ELISAs were performed. All selected phage were bound by the selecting antibody (Figure 1). R4A bound only those phage isolated by selection with R4A; 52b3 bound much more strongly to 52b3 selected phage than the R4A selected phage. Antibody 95, which differs from R4A by a single amino acid in the heavy chain and from 52b3 by four

amino acids in the heavy chain, and has no detectable finding to dsDNA, did not bind to any of the phage clones recognized by either R4A or 52b3.

B. Peptides are Mimetics for dsDNA.

To determine whether peptide and dsDNA bound within the same antigen binding site of each antibody, inhibition assays were performed with specific peptides. Calf thymus DNA inhibited the binding of R4A and 52b3 to R4A and 52b3 selected phage, respectively (Figure 2). In addition, selected phage inhibited the binding of antibody to dsDNA. These were used in fluid phase to inhibit the binding of antibody to dsDNA. Two peptides, ~~Asp-Trp-Glu-Tyr-Ser-Val-Trp-Lys-Ser-Asn~~ B3 and Asp-Trp-Glu-Tyr-Ser SEQ ID NO:2 were chosen as the R4A specific epitope; the 52b3 specific peptide was Arg-His-Glu-Asp-Gly-Asp-Trp-Pro-Arg-Val (SEQ ID NO:7). Each peptide inhibited dsDNA binding by the appropriate antibody only (Figure 3). This result confirmed that the peptides were dsDNA mimotopes binding in or very close to the same site as dsDNA and also emphasized the utility of peptides as probes for differences in the antigen binding pocket of highly related antibody molecules.

C. Blocking of *in vivo* Binding of an anti-dsDNA Antibody to the Kidney by Peptides.

The abrogation of binding was assayed by R4A, as glomerular binding is what is most commonly found among lupus anti-DNA antibodies. Since peptides synthesized from D amino acids are more resistant to proteolytic digestion and have a longer half life *in vivo*, the ability of the R4A-specific peptide DWEYS made from D amino acids to inhibit binding of R4A to dsDNA was assayed. The D and L peptides of DWEYS (SEQ ID NO:2) both inhibited dsDNA binding, although the L peptide showed greater maximal inhibition (see Figure 4).

D. R4A-Specific Peptide Inhibits R4A Deposition in Glomeruli.

To assess whether peptides that bind to anti-dsDNA antibodies have a potential therapeutic application, it was examined whether the DWEYS (SEQ ID NO:2) peptide inhibits R4A deposition in the kidney. Simultaneous injection of 75 μg of purified R4A

antibody and 150 μg of DWEYS (SEQ ID NO:2) as either the L or D peptide was done i.p. into SCID mice (five mice in each group) and immunoglobulin deposition was assessed in glomeruli 15 hours later. The D peptide DWEYS (SEQ ID NO:2) markedly inhibited the deposition of R4A in the kidney, whereas the L peptide did not (Figure 5). The SCID mice receiving the D and L DWEYS (SEQ ID NO:2) peptides displayed equivalent titers of IgG2b in their sera (data not shown), demonstrating that in each set of animals a similar amount of antibody had entered the vasculature. This observation suggests that the decreased susceptibility of the D peptide to proteolysis allowed a greater proportion of antibody to remain complexed to the antigen and prevented binding to glomerular tissue *in vivo*.

III. Discussion

While it has been documented for several years that antibodies may bind more than one antigen in a single antigen binding pocket, peptide libraries provide an unprecedented opportunity to probe the cross-reactivity of particular antibody molecules. An analysis of the peptides contained in phage isolated by a given monoclonal antibody demonstrates that multiple antigenic epitopes may fit within a single binding site. Furthermore, by using peptide libraries to probe antibody binding sites it has been possible to show that an anticarbohydrate antibody can also bind a peptide mimotope (Devlin, et al., Science 249:404-406 (1990)) and that cross-reactive antigens need not have obviously homologous structures (Balass, M., PNAS 90:10638-10642 (1993); Devlin et al., Science 249:404-406 (1990)). It has been shown that antibodies that bind dsDNA may also bind peptide antigens. Both R4A and 52b3 were isolated as dsDNA binding antibodies and both have been shown to bind peptide also. This binding appears by competitive inhibition studies to be within the same site in which dsDNA binds. Furthermore, the peptides bound by R4A are distinct from those bound by 52b3 even though the antibodies are highly homologous, differing by only 3 amino acids in the heavy chain variable region. A second surprising result is that 95 which differs by only a single amino acid from R4A and four amino acids from 52b3 but has no reactivity with dsDNA binds neither R4A nor 52b3 selected peptides. Both R4A and 52b3 bind anionic peptides which is consistent with DNA also having a

negative charge. However, 95 which is more cationic reflecting a Asp to Gly substitution in CDR3 of the heavy chain, does not bind these anionic peptides. Thus the negative charge is not sufficient for these peptides or for dsDNA binding to 95.

The motifs for both pathogenic antibodies have the Asp/Glu-X-Asp/Glu sequence, suggesting that although acidic residues are important in binding, they do not define the fine specificity difference that causes R4A to deposit in glomeruli and 52b3 to deposit in tubules. It is also noteworthy that both the R4A and 52b3 peptides have aromatic residues, tryptophan and tyrosine. The acidic residues, while apparently important in biding to these anti-DNA antibodies, do not define the fine specificity difference that causes R4A to deposit in glomeruli and 52b3 to deposit in tubules. This apparent difference in specificity is consistent with the finding that they bind distinct peptides. It is also noteworthy that both the R4A and 52b3 consensus motifs have aromatic residues, tryptophan and tyrosine. It is tempting to speculate that the negatively charged aspartate and glutamate residues are analogous to phosphate groups, the aromatic tryptophan residues are analogous to the pentose sugar backbone, and the tyrosine and serine residues are analogous to the hydroxyl groups attached to the pentose moiety in the DNA molecule, thus explaining why these peptides are mimics of DNA. One potential utility of identifying peptide mimotopes for dsDNA is to try to determine if the actual eliciting antigen for production of these antibodies or target antigen for deposition in kidneys might be a protein molecule. A search for amino acid sequences with homology to the consensus sequence identified for the R4A and 52b3 monoclonal antibodies revealed that the entire R4A sequence, Asp-Trp-Asp-Tyr-Ser (SEQ ID NO:2) is found in a splice variant of chicken collagen XIV (Walchli, et al., <u>Eur. J. Biochem.</u> 212:483-490 (1993)). It is interesting to speculate whether the murine homolog of chicken collagen XIV also has a splice variant containing the same or highly homologous peptide sequence that would be recognized by the R4A antibody. The DWEYS peptide (SEQ NO:2) can indeed be designated a dsDNA mimotope, as immunization of nonautoimmune BALB/c mice with peptide in complete Freund's adjuvant leads to production of anti-dsDNA antibodies (unpublished work).

One potential use of peptide surrogates for dsDNA is to try to block binding of anti-DNA antibodies to renal tissue *in vivo*. Administration of R4A *in vivo* with a peptide surrogate for dsDNA composed of D amino acids markedly inhibited anti-dsDNA antibody deposition in the kidney of SCID mice. It has been shown that some anti-peptide antibodies will bind peptides in the D as well as the L form (Verdoliva, et al., *J. Biol. Chem.*, 270:30422-30427 (1995); Nomizu, et al., *J. Biol. Chem.*, 267:14118-14121 (1992), while others do not (Schumacher, et al., *Science*, 271:1854-1857 (1996)). As the basis for isoform cross-reactivity is not currently clearly understood, it is not possible to predict which antibodies will react with both the D and L form of a given peptide. However, both the D and the L DWEYS peptide (SEQ ID NO:2) inhibited the binding of R4A to dsDNA. It is interesting to note that while the L peptide inhibited dsDNA better than the D peptide *in vitro*, only the D peptide conferred renal protection *in vivo*, presumably because the D peptides was more resistant to proteolysis in the plasma and had a longer half-life. This likely allowed the D peptide to remain complexed with the glomerulotropic R4A antibody and prevent its deposition in the kidney.

In this *in vivo* study, peptide was used in a high molar ratio to antibody. Because the actual concentration of nephritogenic antibody is low in serum, a high ratio of peptide to nephritogenic antibody might be achievable in humans. In SCID mice, it could not be assessed whether the peptides themselves were immunogenic. This is unlikely, however, as monovalent soluble antigens are poorly immunogenic; rather, it is possible that they will be tolerogenic for B cells producing antibodies that react with the peptide.

The finding that peptide can markedly inhibit deposition of R4A in glomeruli *in vivo* suggests a therapeutic strategy. It will be necessary first, however, to determine the heterogeneity of the binding sites of nephritogenic anti-DNA antibodies. Although it is known that these antibodies are encoded by multiple variable regions, it is not clear how extensively they differ in fine antigenic specificity. For example, the screening of nephritogenic antibodies with peptide libraries might reveal

a limited number of specificities. While the exquisite specificity of the peptides for individual binding sites may suggest this is unlikely, it is also possible to sequentially screen libraries with different antibodies to seek a peptide that recognizes common shared conformations in different though related antibody binding sites (Valadon, et al., *J. Mol. Biol.* 261:11-22 (1996)). If a small panel of peptides could be identified that inhibits the binding of the anti-dsDNA antibodies in the serum lupus-prone mice, or of patients with systemic lupus erythematosus, then it is possible that peptides can provide a significant therapeutic option.

All publications mentioned hereinabove are hereby incorporated in their entirety.

While the foregoing invention has been described in some detail for purposed of clarity and understanding, it will be appreciated by one skilled in the art from a reading of the disclosure that various changes in form and detail can be made without departing from the true scope of the invention in the appended claims.

Summary of Biopanning

Antibody	Concentration (nM)	Selection Round	Phage Yield (%) with antibody	Phage Yield (%) control	Amplification
R4A	1000	1	6.3×10^{-3}		
	10	2	1.5×10^{-4}	5.7×10^{-5}	2.6
	10	3	1.1×10^{-2}	1.6×10^{-4}	690
52b3	1000	1	2.0×10^{-2}		
	10	2	1.6×10^{-2}	1.7×10^{-3}	9.6
	10	3	8.9×10^{-2}	1.4×10^{-3}	65
	10	4	6.5×10^{-2}	2.7×10^{-4}	239

Table 1. Yield of phage following biopanning with R4A and 52b3.

B34

Table 2

Phage	Sequence	SEQ ID NO:	Frequency	Binding O.D. 405 nm
ϕ1-3	D W E Y S V W L S N	1	23	1.3
ϕ7-21	W C E A D Y G R C P	8	23	1.3
ϕ7-6	L Y F E D Y R C E L	9	3	1.2
ϕ7-3	D W D Y G A L M W A	10	1	1.1
ϕ1-10	Y S D W D Y S E G L	11	1	1.1
ϕ1-2	S T E H S E A D L W	12	8	0.7
ϕ7-26	V P V C D W E L N C	13	1	0.4
Consensus:	D/E W D/E Y S/G	2		
ϕ1-1	F S D C Y H S G C P	14	3	1.5
ϕ3-3	No insert			0.1

Table 2. Randomly selected sequences obtained by biopanning a decapeptide library with R4A. A total of 75 phage were sequenced.

InsB4

Phage								Sequence								Frequency	Binding O.D. 405 nm
Φ1-3						D	W	E	Y	S	V	W	L	S	N	23	1.3
Φ7-21				W	C	E	A	D	Y	G	R	C	P			23	1.3
Φ7-6				L	Y	F	E	D	Y	R	C	E	L			3	1.2
Φ7-3						D	W	D	Y	G	A	L	M	W	A	1	1.1
Φ1-10				Y	S	D	W	D	Y	S	E	G	L			1	1.1
Φ1-2	S	T	E	H	S	E	A	D	L	W						8	0.7
Φ7-26		V	P	V	C	D	W	E	L	N	C					1	0.4
Consensus:						D/E	W	D/E	Y	S/G							
Φ1-1						F	S	D	C	Y	H	S	G	C	P	3	1.5
Φ3-3						No insert											0.1

Table 2. Randomly selected sequences obtained by biopanning a decapeptide library with R4A. A total of 75 phage were sequenced.

Table 3

52b3 Selected Phage

Phage	Sequence	SEQ ID NO:	Frequency	Binding O.D. 405 nm
ϕB11	R H E D G D W P R V	7	1	1.4
ϕB25	L L D D G F W P R V	15	1	1.5
ϕB23	C G V D G R W P R W	16	1	1.5
ϕB24	S L I S D E W P R W	17	1	1.3
ϕB56	D G E W P R E G W S	18	1	1.6
ϕB22	E D L E G E W P M R	19	1	1.5
ϕB1	S L D E L D W D S M	20	4	1.4
Consensus:	D/E G D/E W P R	5		
ϕB16	T W C P V W I W D C	21	1	1.0
ϕB17	V L I C W D G C E T	22	1	1.6
ϕB21	W D C Y V C R L E L	23	1	1.2
ϕB52	S C Y Q S Y P G E C	24	1	1.8
ϕ3-3	No insert			0.4

Table 3. Randomly selected sequences obtained by biopanning a decapeptide library with 52b3. A total of 33 phage were sequenced.

Table 3

52b3 Selected Phage

Phage	Sequence													Frequency	Binding O.D. 405 nm
ΦB11	R	H	E	D	G	D	W	P	R	V				1	1.4
ΦB25	L	L	D	D	G	F	W	P	R	V				1	1.5
ΦB23	C	G	V	D	G	R	W	P	R	W				1	1.5
ΦB24	S	L	I	S	D	E	W	P	R	W				1	1.3
ΦB56				D	G	E	W	P	R	E	G	W	S	1	1.6
ΦB22	E	D	L	E	G	E	W	P	M	R				1	1.5
ΦB1	S	L	D	E	L	D	W	D	S	M				4	1.4
Consensus:				D/E	G	D/E	W	P	R						
ΦB16	T	W	C	P	V	W	I	W	D	C				1	1.0
ΦB17	V	L	I	C	W	D	G	C	E	T				1	1.6
ΦB21	W	D	C	Y	V	C	R	L	E	L				1	1.2
ΦB52	S	C	Y	Q	S	Y	P	G	E	C				1	1.8
Φ3–3	No insert														0.4

Table 3. Randomly selected sequences obtained by biopanning a decapeptide library with 52b3. A total of 33 phage were sequenced.